BENTON HARBOR POWER PLANT LIMNOLOGICAL STUDIES.

PART I. GENERAL STUDIES.

November, 1967

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Under Contract With:

American Electric Power Service Corporation

A. INTRODUCTION AND OUTLINE OF PROGRAM

In response to a specific request from Mr. Paul Dragoumis, this report has been prepared prior to the completion of the studies contracted.

On the basis of the results to date, we believe that the study of the relationship of wind to current direction in the alongshore waters in front of the plant site is the only important task yet to be completed.

We, therefore, present this report as Part I of the total report of the contract. Part II, consisting of the results of the wind-current relationship in the alongshore waters of the AEPSC site, will be presented at a later date.

As a result of the request to report earlier than contracted, there is omitted one item which would have been a part of this report under normal conditions. This item is the preparation of an annual curve of air temperature for 1966. The air temperature curve is needed for comparison to water temperature curves, presented here, in determining seasonal variation in the ability of the local air-water environment to remove thermal load from the plant effluent.

Our sincere thanks for assistance rendered are expressed to Messrs. Paul Dragoumis and J. E. Gingold. Especial thanks for assistance rendered at his own inconvenience are given to Mr. John Banyon.

Work Plan and Its Status

The program of work planned for the limnological surveys relative to the Benton Harbor generating plant consisted of the

eight numbered items below. The present status of each item is shown.

1. Bathymetric survey off site, including consideration of bottom stability.
   Complete and reported, including early-spring check on effect of winter ice on the nature and position of the sand bars.

2. Bottom-type survey off site.
   Complete and reported.

3. Determination of alongshore current direction under various wind directions.
   Delayed by inability to obtain required instruments and by winter ice. Now under way.

4. Determination, by dye dilution experiments, of the inherent diluting capacity of alongshore currents at the site.
   Some runs have been made, more can be made if required.

5. Determinations of the locations of local potable water intakes and of the possibility of plant effluent reaching them.
   Complete and reported.

6. Ecological study of thermal pollution and its effects.
   Will be handled by Dr. C. F. Powers. As a basic preliminary to this study the numbers and distributions of bottom-living organisms off the plant site have been determined and reported.

7. Estimates of dilution and dispersion of thermal effluent from the plant.
   Completed and reported, but will be amended if work now under way permits better estimates.

8. Studies of unusual conditions. Extraordinary seiches are the only item in this section.
   Completed and reported.

B. PHYSICAL LIMNOLOGY

1. REGIONAL FEATURES

The Berrien County power plant site is located on the southeastern shore of Lake Michigan in a region where land topography and lake-bottom topography both show the effects of glaciation.

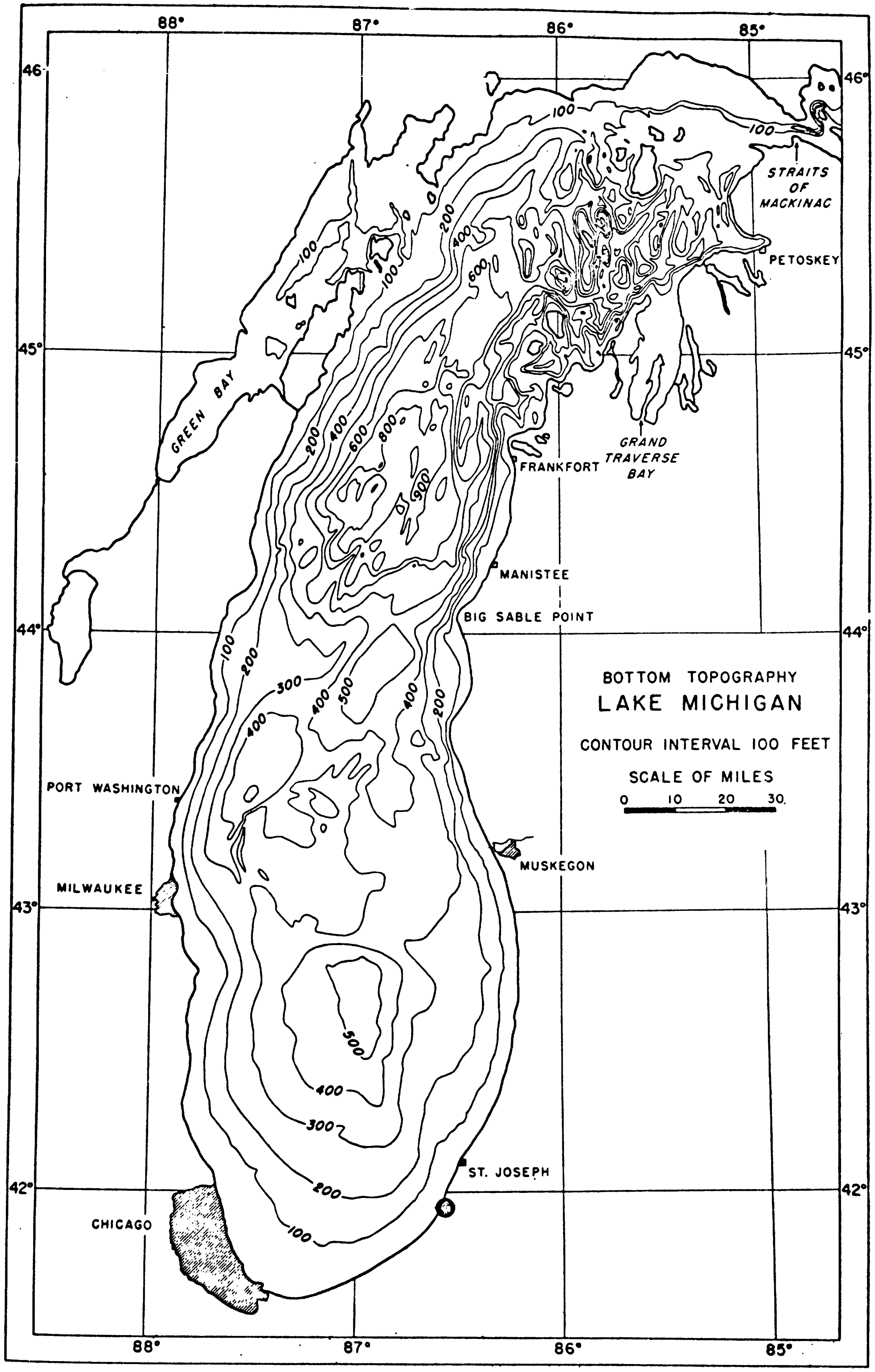
The lake-bottom topography (bathymetry) has been subject to the smoothing erosional and depositional actions of the lake water since recession of the last glacier. This smoothing action has been last to happen after the gouging and scouring actions of the glacier itself and after the water-laid deposition of sediments released from the glacier ice during melting and recession of the ice. From the sediment-sorting actions of the water there has further followed the development of a much more regular distribution of sediment types than is the case on land.

Bathymetry

The basin of Lake Michigan as a whole is divided by an incomplete sill of resistant materials extending from the region of Milwaukee, Wisc., toward Muskegon, Mich.; this incomplete sill establishes two sub-basins called herein the northern and southern basins. While both basins show the smoothing actions of the lake water, the northern basin is deeper, more elongate and of more irregular bathymetry while the southern basin is shallower, rounder and of more regular bathymetry. Figure 1 is a recent chart of the bathymetry of Lake Michigan.

Sediment Types

In both basins of Lake Michigan the basic progression of bottom surface-sediment types is from sands or sand and gravel in a relatively wide belt along the beaches, to silty sands in a narrower more irregular belt in shallow intermediate depths, to sandy silts in a variable discontinuous band in deeper intermediate depths, to soft combinations of silts and clays and loam (sandy



The bottom topography of Lake Michigan.
(from Hough 1958)

FIG. 1

~~FIG. 2.6.1~~

silty clay) in the deepest portions. Figure 2 is the best recent chart of sediment types and shows this basic distribution of sediments.

Benthos

The bottom-living organisms (benthos) of the lake respond, in their degree of abundance, to a combination of sediment type and organic richness of the overlying water. By "organic richness" is meant the presence of decomposing and decomposed "natural" organic materials from the lake's watershed and "artificial" organic materials from man's wastes. These organic materials provide fine organic detritus and support bacterial growths, both of which are utilized as food by the bottom-living organisms.

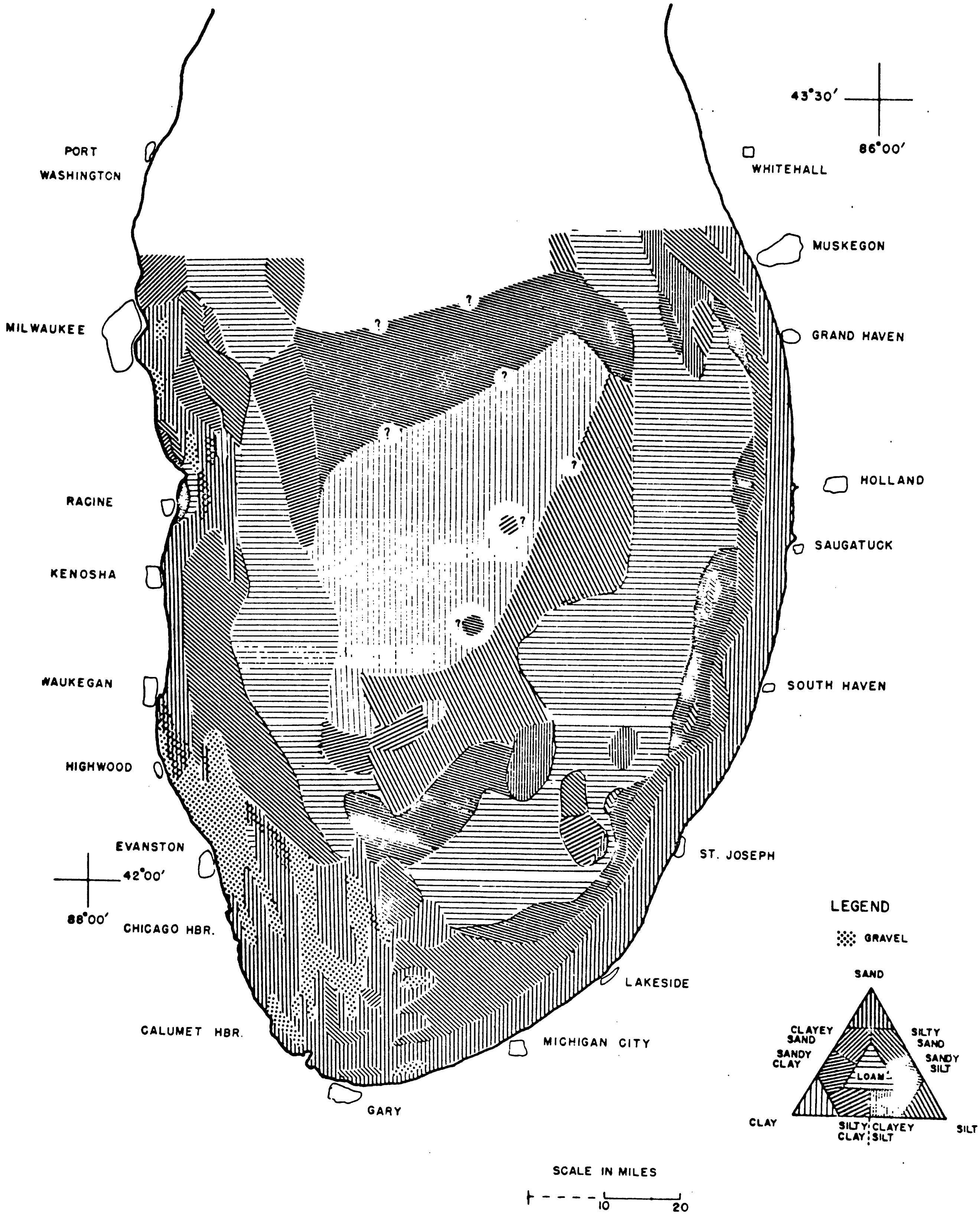
Figure 3 presents our present best knowledge of the distribution and abundance of the normal community of bottom-living organisms in the main part of the lake. There is lack of detailed knowledge in many regions, but we know of disrupted normalcy of the benthos at Milwaukee, in the inshore region from Chicago to Michigan City, and at the mouth of the St. Joseph River. Normal communities of benthos are known from studies by the present project to reach to the Michigan shore in the interval between Michigan City and the St. Joseph River.

The maximum abundance of normal benthos follows the band of silty sand sediments which underlays the alongshore belt of currents that receives the decomposition products of natural organic materials and of man's wastes.

Gross Currents

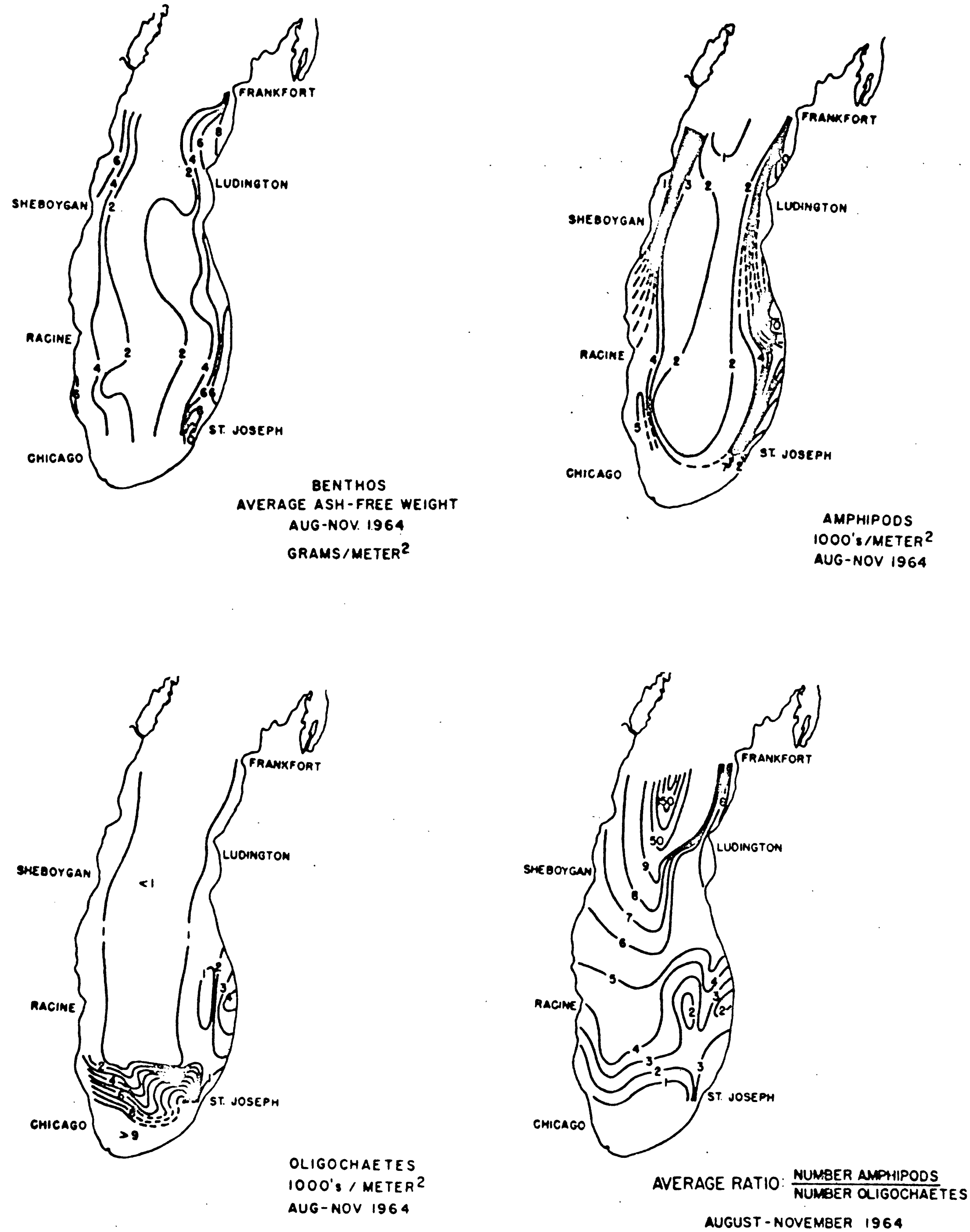
The mass movement of water that is designated as "current" is the primary distributor of everything inanimate that gets into the lake. Although we do not understand the currents of Lake Michigan in detail, there are certain larger features that have been found with a surprising degree of consistency. The two most firmly established of these features are a general outflow current along the Michigan shore from Little Sable Point northward toward the Straits of Mackinac, and the presence of a large eddy near the eastern shore off Benton Harbor. Both these features were found in the first significant current study, reported by Harrington in 1895. Deason (1932) deduced the presence of something like the Benton Harbor eddy. Ayers et al (1958) found both the eddy and the outflow current in surveys in 1955. Bellaire (1964) also found them both. Ayers et al and Bellaire disagree with Harrington as to the direction of rotation of the Benton Harbor eddy (Fig. 4), while Deason shows no figure and speaks only of a "swirling action" in the southeast portion of the lake.

While none of these studies were designed to delineate circulation immediately close to shore, they agree in the establishment of a major current feature close in to shore in the southeast corner of the lake. Ayers et al (their Fig. 24) tentatively identify a thin elongate counterclockwise eddy close against shore between Michigan City and Benton Harbor (indicated by an X in Fig. 4). This eddy may be pertinent to the alongshore currents at the plant site. The matter is discussed later.



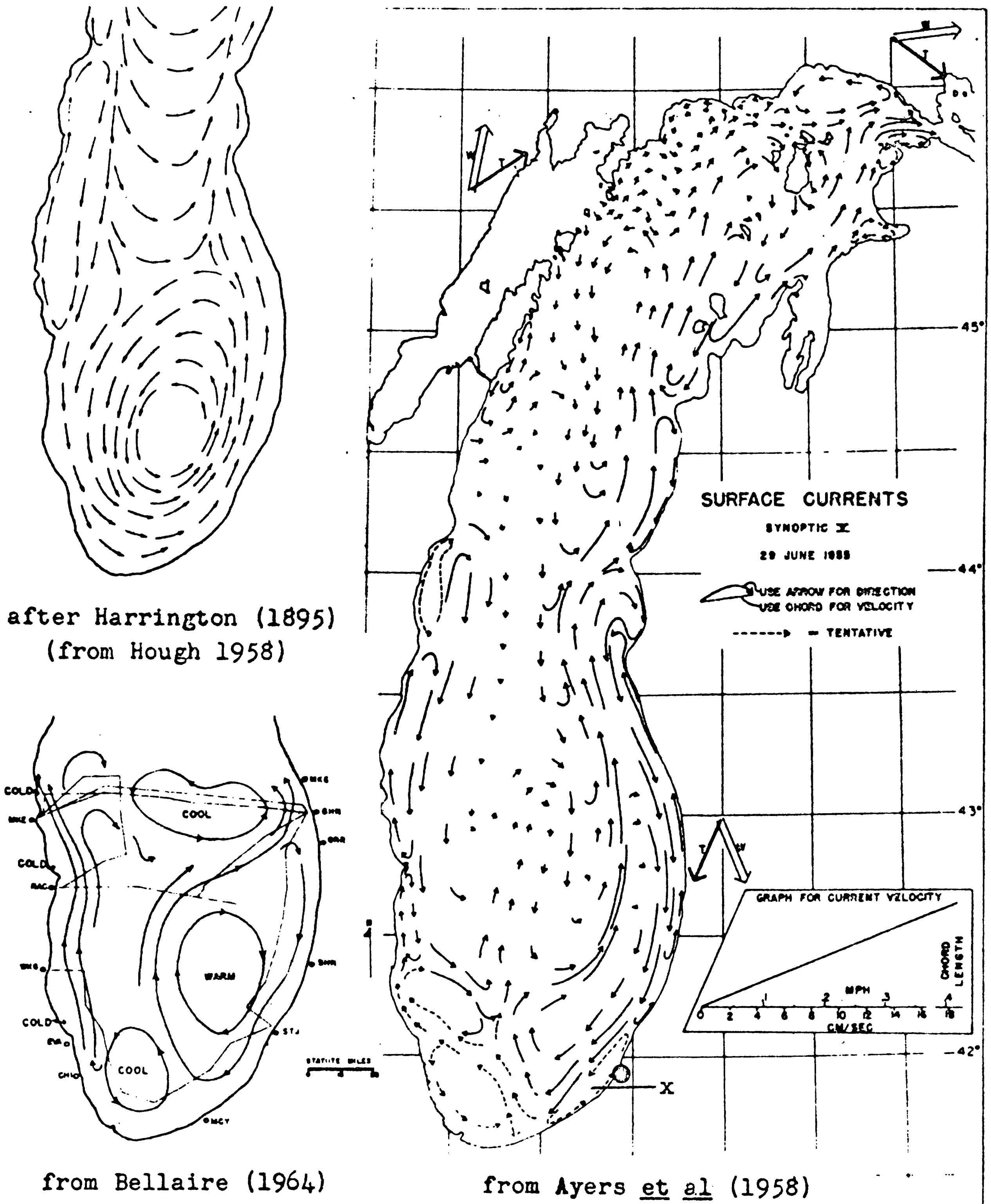
The bottom sediments of Lake Michigan in 1962-1963.
(from Ayers and Hough 1964)

Figure 2



Distributions of bottom-living organisms in Lake Michigan.
(from Powers and Robertson 1965)

Figure 3



Three concepts of the surface currents of Lake Michigan.

FIG. 4

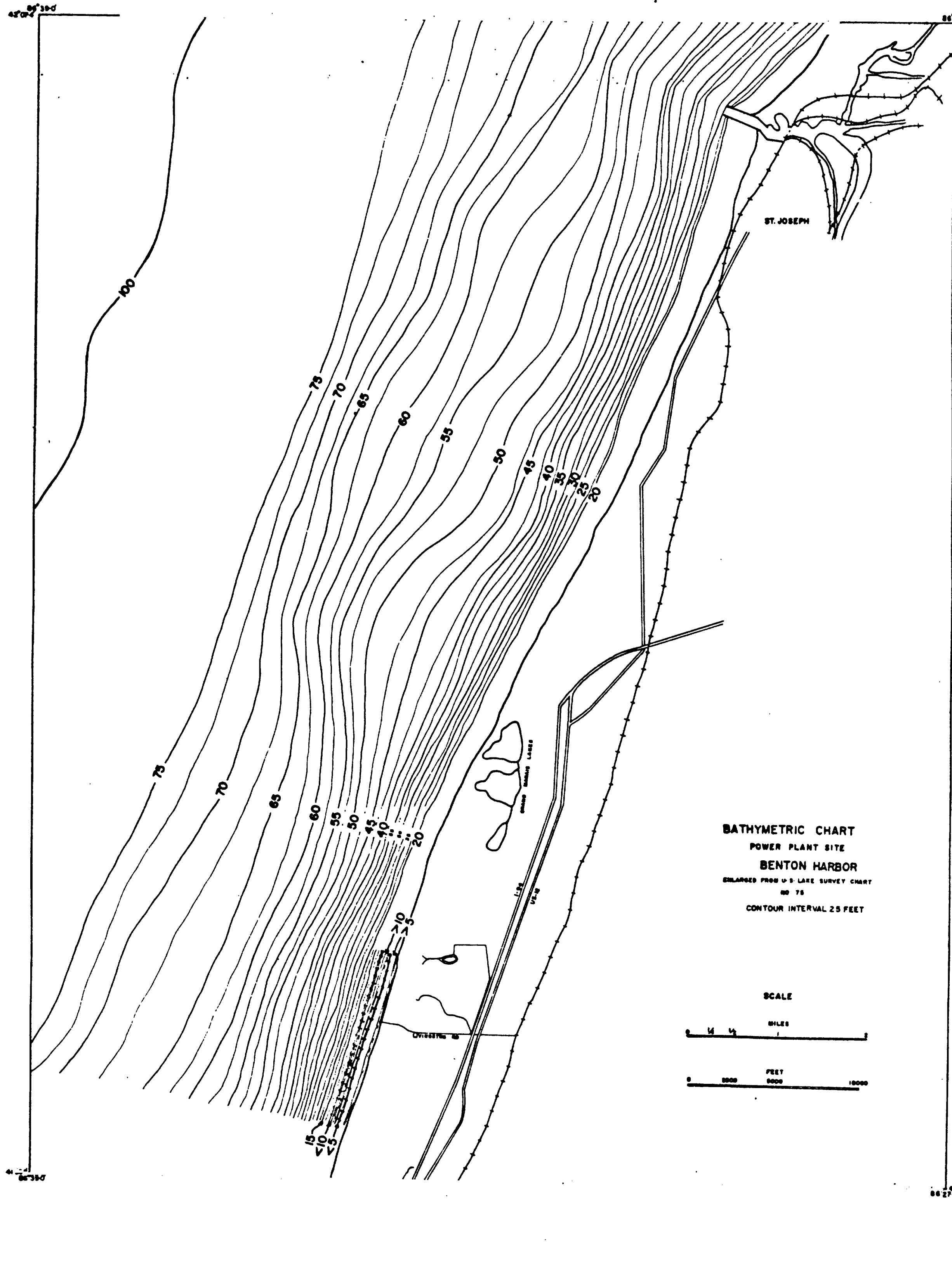
2. LOCAL FEATURES

Local Bathymetry

The local distribution of water depth was surveyed in May, June and July 1966 from north of the mouth of the St. Joseph River to south of the plant site. The region is characterized by gentle and regular bottom topography (Fig. 5). The 100-foot depth isopleth lies at about six miles from shore. Isobaths less than 40 feet are regular and parallel to the shoreline. Isobaths between 40 and 75 feet exhibit some irregularities between St. Joseph and Grand Marais Lakes, becoming regular and essentially parallel to shore south of Grand Marais Lakes.

In the whole extent of the survey there were two sand bars close to shore. They have been subject to spot tests between the plant site and St. Joseph, but not in detail sufficient to warrant their charting. Along the front of the plant property and to one mile south of Livingston Road these bars have been surveyed in sufficient detail to chart. They are shown in front of the plant property and to the south boundary of the survey in Figure 5. The inner bar averages about 500 feet from water's edge over the area of detailed survey, but lies slightly nearer to shore off the north edge of the plant property. At the north edge of the site a taut-wire measurement on 13 September showed the inner bar to be about 450 feet from water's edge. The 500-foot distance from the beach edge at the point fell into 11 feet of water outside the crest of the inner bar.

The outer bar lies about 1000 feet from water's edge at the north edge of the plant site. It is situated about 1100 feet off



BATHYMETRIC CHART
POWER PLANT SITE
BENTON HARBOR
CONTOUR INTERVAL 2.5 FEET
SCALE
MILES
FEET
ST. JOSEPH
100
75
70
65
60
55
50
45
40
35
30
25
20
15

FIG. 5

~~FIG. 2.6-3~~

shore at Livingston Road, but at the south edge of the survey it again lay at 1000 feet off shore.

Maximum water depth of 5-6 feet is present between the inner bar and the shore. Twelve to thirteen feet of depth is the greatest that was measured between the two bars.

Outside the crest of the outer bar the bottom falls slowly; 20 feet of depth is attained at about 1700 feet off shore at the north edge of the plant property. Over the rest of the detailed survey about 1800 feet from shore was needed to reach 20 feet of depth.

The depth over the crest of the inner bar is about four feet. The outer bar peaks at 8-9 feet beneath water surface.

Bottom Stability

Our own bathymetric surveys in May, June, and July plus an additional visit to the site on 13 September all showed the two sand bars to be in the same positions and with the same depths of water over their crests and in the troughs.

This suggestion of stability of the bottom, insofar as possible migration of sand bars is concerned, is in agreement with the findings of Davis and McGeary (1965). In June and August of 1963 they carried out detailed underwater studies of the topography and sediment distribution in two sites in Michigan on southeastern Lake Michigan. One of their study sites was in Berrien County, the other in Allegan County. The Berrien County site was between Union Pier and Bridgman, Mich.

Davis and McGeary found that no distinction existed between data collected before and after this two-month interval in summer

during which the normal summer storms occurred. The offshore bars remained constant in relationship to the shore and showed only small variations in profile shape. Indices of water depth, mean sediment grain size and of sediment sorting showed little change, all indicating relative stability of the alongshore topography.

In addition to the studies above, Davis and McGeary examined aerial photographs of their study sites that had been taken in 1953 and in 1960. As near as they could determine the bars were then in the same position as in 1963.

So far as we can determine no one with the possible exception of Evans (1940) has examined the alongshore topography early in the spring to ascertain whether winter storms or ice have produced topographic changes.

Evans believed that the bar and trough topography in the alongshore of eastern Lake Michigan was not appreciably changed with time. Evans' studies were carried out in Lake Michigan from the city of New Buffalo to Grand Traverse Bay using five different methods through two years. Over a period of about 14 months he observed that little or no movement of the well-established sand bars occurred. Even after a heavy storm with high winds of more than 35 mph which lasted 36 hours on August 8-9, 1939, there was no general migration of the trough and bars in either direction. Evans' hypothesis was that sand bars are deposited by the plunging type of breaking waves, which stir up sediments from the bottom and move most of them in the windward direction. Oscillation waves which produce plunging breakers of sufficient size to affect the inner bars may pass over the outer bar without breaking. Such

waves have little or no effect on the trough and outer bar. If water-level falls, the inner bar will begin migrating toward shore as soon as its top comes within the sphere of action of plunging wave crests.

In the southern area of Lake Michigan oscillation waves and small water level fluctuation are common. Therefore, the inner bar which is about 450-500 feet offshore in the site area is subject to slightly more potential migration force than is the outer bar.

The Bars on 30 March 1967

On 30 March 1967 the RV MYSIS made a check on the presence and condition of the two sand bars within a few days of breakup of the shore ice.

As near as could be determined from sextant fixes on landmarks on shore both the bars were in the same position as in September 1966. Both the bars had the same depth of water over them as in September.

Local Sediment Types

During July of 1966 we surveyed the bottom sediments of the local area from the mouth of the St. Joseph River to a mile and a half south of Livingston Road at the south boundary of the plant property. Lines were run to three miles off the beach and were spaced at half-mile intervals. The results are shown in Figure 6.

The predominant sediment of the bottom over the area was fine sand, either silty and with visible organic material, or non-silty and with organic material. In several places there was sufficient

of a brown mineral (probably hematite) to cause the observer to note "speckled" in his reading of the sands.

One sample of coarse sand was taken off Livingston Road, and a couple just below the mouth of the St. Joseph River.

Medium sand was taken in a few samples along the beach south of the mouth of the St. Joseph River. It was also taken in a somewhat larger area at the outer edge of the survey northwest of Grand Marais Lakes. One sample was also taken off the north edge of the plant property.

Soft grey loam (sand-silt-clay) was taken in a few samples west of Grand Marais Lakes, and northwest and north of those lakes. The sand of these loams was fine sand.

Except for the predominance of silty and non-silty fine sands, there are only two items of ecological interest: the widespread occurrence of organic material with a local area of abundance southwest of the mouth of the St. Joseph River, and a definite area of sandy silt surrounding the mouth of that river. Cook and Powers (1964) studied the effect of the St. Joseph on the bottom-living organisms. At stations around the river mouth they found these organisms to be dominantly pollution-tolerant forms, and speculated that organic solids contributed by the river should modify the sediments near the river mouth. We find that modification to be present.

The Local Benthic Organisms

On 13 and 15 July 1966, we surveyed the local population of bottom organisms. The survey consisted of collecting samples in a regular fashion in lines perpendicular to the beach. The survey

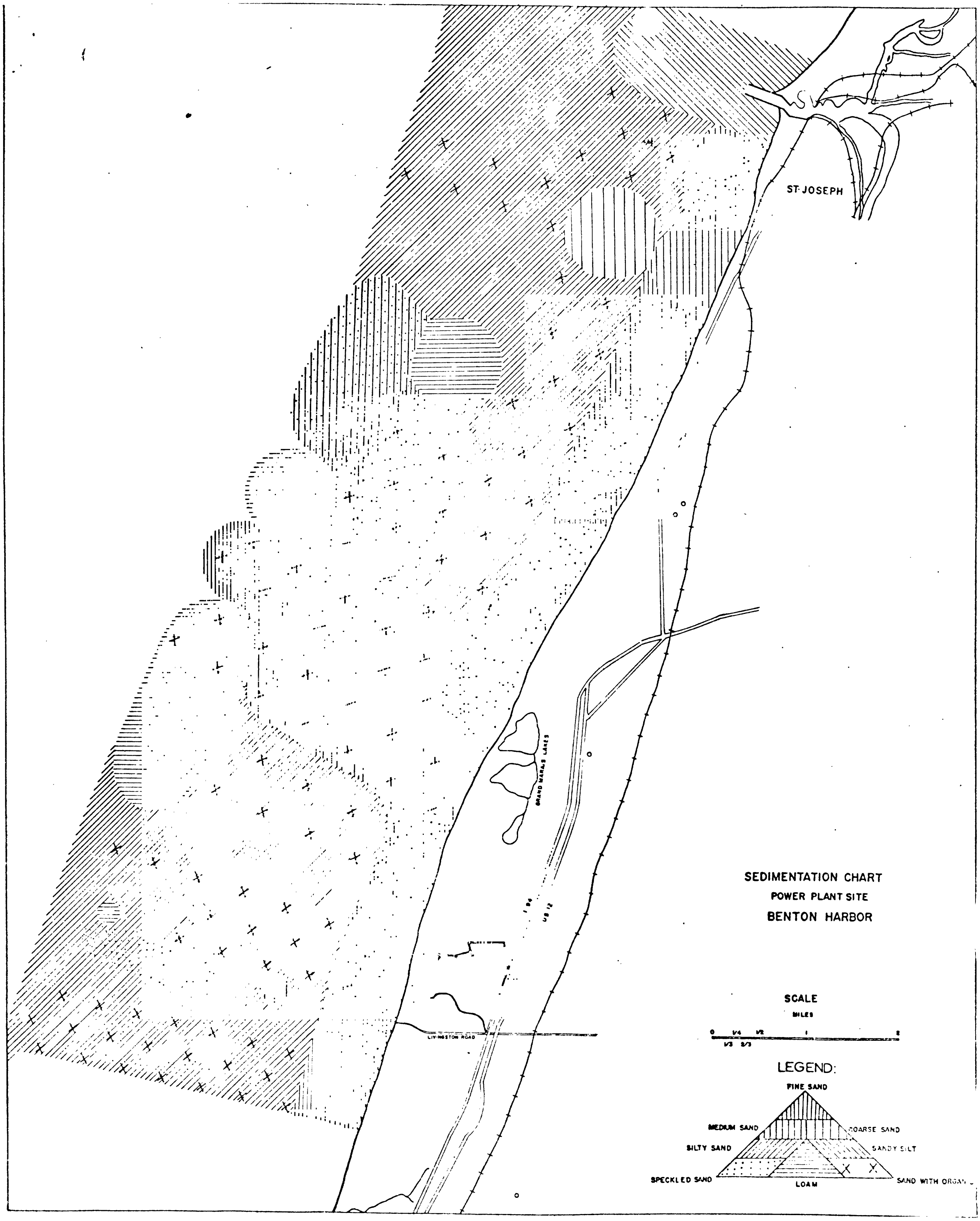
began at the mouth of the St. Joseph River and extended to a line a mile south of the site property. In each line the inshore samples were taken in 15 feet of water with other samples at 1 mile, 2 miles, and 3 miles off the beach. From the river mouth to the north edge of the plant property sampling lines were one mile apart. In front of the site the interval between lines was reduced to a half-mile.

Samples were taken by grab sampler and washed through a sieve of 0.5 mm mesh. Organisms retained by the sieve were preserved in formalin and sorted, counted, and processed in the laboratory. A total of 60 stations were sampled, and samples off the site property were taken in triplicate and averaged.

The parameters determined were the same as used by Powers and Robertson (1965) in their surveys of the main body of the lake. The parameters reported here are 1) ashfree dry weight of all organisms (as the best measure of the mass of organic matter of the animals, free of shells, sand, etc.), 2) numbers of amphipods (also commonly called aquatic scuds or freshwater shrimp) in thousands per square meter of bottom surface, 3) numbers of oligochaetes (also called aquatic earthworms, tubificids, or sludgeworms) in thousands per square meter, and 4) the ratio at each station of numbers of amphipods over numbers of oligochaetes.

The distributions of these parameters are shown in Figure 7.

The distribution of mass of benthic-organism tissue (Fig. 7A) is evidently related in substantial degree to sediment type. Low weights of organism tissue were present in the clean sands of the area immediately next to the beach. Low weights were also found



ST. JOSEPH
GRAND MARAIS LAKES
I 94
US 12
LIVINGSTON ROAD
SEDIMENTATION CHART
POWER PLANT SITE
BENTON HARBOR
SCALE
MILES
0 1/4 1/2 1 2
1/3 2/3
LEGEND:
FINE SAND
MEDIUM SAND
COARSE SAND
SILTY SAND
SANDY SILT
SPECKLED SAND
LOAM

FIGURE 6

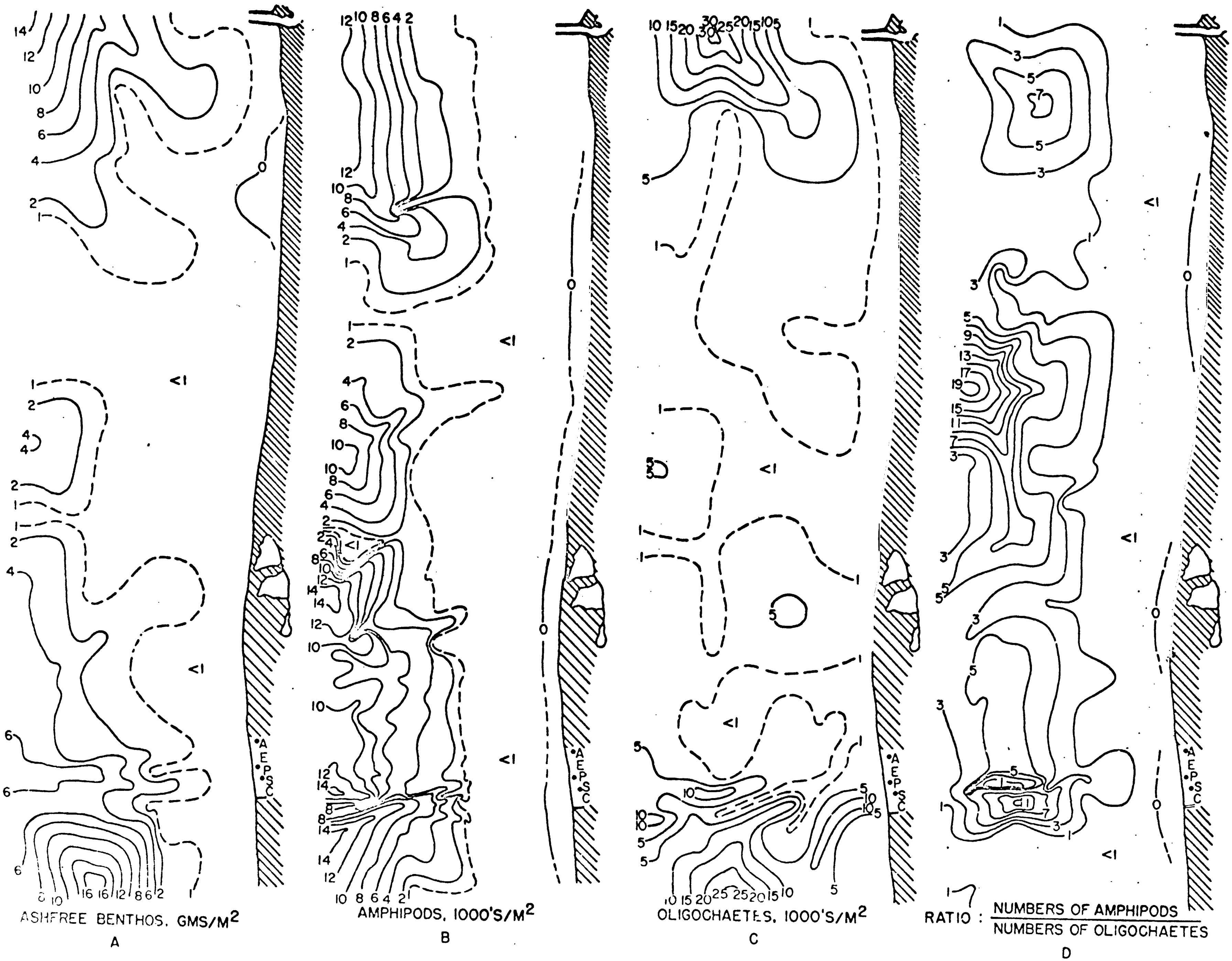

ASHFREE BENTHOS, GMS/M^2
A
AMPHIPODS, 1000'S/M^2
B
OLIGOCHAETES, 1000'S/M^2
C
RATIO : $\frac{\text{NUMBERS OF AMPHIPODS}}{\text{NUMBERS OF OLIGOCHAETES}}$
D

FIGURE 7

in the sandy silt region extending a mile off the mouth of the St. Joseph River.

High quantities of organism-tissue were in most cases correlated with bottom areas of silty fine sand. The two areas of maximum biological mass lay in silty fine sand two and three miles off the mouth of the river, and at the second and third miles offshore south of the property. An area of less organism mass lay in silty medium sand and in loam west of Grand Marais Lakes.

Northwest of Grand Marais Lakes there was an extensive region that yielded less than one gram of organisms per square meter and which reached offshore through the three-mile grid of sampling stations.

There was no evident relation between the mass of benthic-organism tissue and the presence of organic material in the surface sediment.

In all but one case the presence of speckled sand correlated with low quantities of biological mass. The meaning of this relation is not clear.

In general, the distribution of the quantities of the whole benthic population appears to be typical of the clean-water portions of Lake Michigan. The low population in the first mile off the beach is normal. There is, in the present natural condition, no unusual concentration of benthic organisms near shore that would attract fish in unusual numbers.

The distribution of the amphipod, Pontoporeia affinis, over the survey area is shown in Figure 7B.

High numbers of this organism coincide with areas of silty

sand and of loam. Low numbers were present in the sandy silt area at the mouth of the river and in the belt of wave-washed sands along the shore. In most cases, areas of speckled sand contained low numbers of amphipods.

The presence of Pontoporeia in goodly numbers in the second and third miles from shore is normal for the unpolluted portions of Lake Michigan. This organism is commonly regarded as an indicator of clean water. Its virtual absence near the beach indicates only unfavorable conditions of wave-action, not unclean water.

The distribution of oligochaetes is shown in Figure 7C.

Some of these organisms are tolerant to organic pollution, and extremely high numbers of them are commonly considered to be an indication of polluted waters.

The maximum numbers found, 31,000/m^2 off the river mouth, 29,700/m^2 in the south edge of the surveyed area, and 14,500/m^2 and 14,400/m^2 off the south side of the property, are reflections of organic matter in the sediments and water and of suitable sediment types. These numbers, though large, are not in the hundreds-of-thousands/m^2 that indicate polluted water.

Wave action in the belt along the beach is probably the cause for low numbers of oligochaetes there, for they are soft-bodied and wave-caused sand movement is injurious to them.

In Figure 7D is presented the distribution of the ratio: numbers of amphipods/numbers of oligochaetes. This is basically a measure of clean-waterness. High values of the ratio express dominance of the clean-water amphipods; low values indicate

dominance of the pollution-tolerant oligochaetes.

No suggestion of unclean water should be read from the zero values along the beach. These merely reflect the normal absence of amphipods from wave-swept areas.

Three centers of high values are present: southwest of the river mouth, northwest of Grand Marais Lakes, and off the plant property. Lower, but not fractional (less than one), values occur between the centers of high values over nearly all the area surveyed. Only south of Livingston Road do values less than one extend out through the surveyed area. At present we do not interpret these low values as indicating unclean water, for there are high numbers of the clean-water-loving amphipods at these stations (see Fig. 7B). Some factor not now known produces at these stations an unusually high population of the oligochaete worms.

In summary, the evidence given by the benthic organisms is that the waters bordering the property are at present predominantly of the clean-water characteristics found over most of Lake Michigan.

Local Currents

Studies producing estimates of the regional current pattern off the Berrien County shore of Lake Michigan were carried out by Harrington (1895), Deason (1932), Ayers _et al_ (1958) and Bellaire (1964). These have been discussed earlier. They define a large eddy of current, called here the Benton Harbor eddy, lying offshore, but close to shore, and extending from Muskegon or Grand Haven to Michigan City. Interpretations as to the rotation of this eddy have not been consistent. Ayers _et al_ deduced a tentative thin elongate counterclockwise eddy between the larger eddy and the shore

between Michigan City and Benton Harbor.

The directions and speeds of the local water currents in the area of the plant site will control the movement and dispersal of the plant effluent. In other alongshore environments that we have studied in the Great Lakes, the currents alongshore are usually established by and controlled by interactions between local winds and any significant regional current pattern. In the alongshore areas previously studied, the local winds have been the dominant factor in the control of the local currents. We have no reason to expect that this will not be true at the present site, but we have not yet collected sufficient evidence to determine whether the effect of the regional current pattern will be as minor here as it has been at other sites.

Spot-sampling of simultaneous wind and current conditions has been carried on in connection with other portions of the work done off the plant site, but such sampling cannot readily accumulate the very large numbers of observations needed to understand the mechanism controlling the local currents. Especially spot-sampling cannot supply the large series of time-sequence data needed to determine whether present currents are influenced by past winds. Continuously recorded simultaneous wind and current conditions are in progress to obtain the needed data.

Although the recording and analysis of these data have been a matter of dominant interest since the beginning of the contract, we have been prevented from getting at it by simple inability to obtain the necessary instruments. Winter storms and winter shore-ice are almost certain to destroy underwater installations that are anything other than massive; installation of the underwater

current-sensing gear was consequently postponed until spring of 1967.

The little that can be said of the current regime alongshore at the plant site is based upon spot-sampling carried out during summer and fall of 1966. The data presently available are presented in Table 1.

Comparison of the actions of drogues to that of dye on 26 October under SSW wind suggests that the drogues may have been in the offshore edge of the counterclockwise Michigan City-Benton Harbor eddy of Ayers _et al_ while the dye was in the shoreward edge of the same eddy. Similar behavior of the dye sets of 27 October under southwest wind also suggests the presence of the postulated onshore counterclockwise eddy, with the dye in its onshore edge.

The behaviors of the dye patches and drogues on 24 and 25 October under northwest winds are contradictory. Such behaviors might indicate that northwest winds constitute a phase-over condition wherein changeover between two dominant current directions is achieved. Such behaviors might indicate some wind-velocity control of current direction, either in a phase-over direction situation or in a condition in which some critical wind velocity is needed to maintain a current pattern, i.e. the Benton Harbor eddy and associated onshore elongate eddy. The answer cannot be gotten from the data available. The northwest-wind paradox does, however, illustrate why winds and currents are being simultaneously recorded for a long period.

The data available do suggest that plant effluent, if discharged at shoreline or close to shore, will return to the beach

Table 1.

Alongshore Current Direction and Velocity under Winds from Various Directions

Date	Wind		Current Indicator	Time Interval	Distance Travelled	Current		Remarks
	Direction	Speed				Direction	Speed ft/sec	
	N							
19 Sept	NE	20 mph	Dye	2h15m	---	SW	---	No final fix. Set between sand bars.
	E							
	SE							
	S							
26 Oct	SSW	5 mph	Dye	3h45m	1400 ft	030° T	0.10	Set between bars
	SSW	5 mph	Drogue	3h27m	4000 ft	182° T	0.32	1/2 mile from shore
	SSW	5 mph	Drogue	3h16m	5000 ft	174° T	0.43	1 mile from shore
	SSW	5 mph	Drogue	3h04m	6700 ft	157° T	0.61	2 miles from shore
27 Oct	SW	20 mph	Dye	1h55m	1150 ft	020° T	0.17	Set between bars
	SW	20 mph	Dye	1h40m	1250 ft	000° T	0.21	Set outside outer bar
	W							
24 Oct	NW	14 mph	Dye	2h40m	1200 ft	045° T	0.13	Set between bars
	NW	14 mph	Drogue	1h18m	2500 ft	027° T	0.53	Set outside outer bar
	NW	14 mph	Drogue	1h05m	1250 ft	035° T	0.32	Set outside outer bar
25 Oct	NW	5 mph	Dye	5h45m	5300 ft	197° T	0.26	Set between bars
	NW	5 mph	Dye	5h23m	5200 ft	193° T	0.27	Set outside outer bar
13 July	NNW	5 mph	Drogue	5h40m	6600 ft	208° T	0.32	Set between bars

and work along it under the prevailing winds of summer and winter. They further suggest that if the plant's water intake is at distance and at depth comparable to those of the direct-withdrawal water treatment plants of the region there should be limited chance that the effluent could reach the intake.

Local Natural Dilution

Our *in situ* studies of natural dilution rate in the alongshore water off the plant site used the red fluorescent dye, Rhodamine B, in the technique of Pritchard and Carpenter (1960). Stock dye in a 40% solution in acetic acid was used. It has a small negative buoyancy and requires dilution with an alcohol to become neutrally buoyant. Our dye sets consisted of one quart of the dye stock diluted with six quarts of methanol antifreeze. Dilutions were made in a plastic garbage can and introduced by gently lowering the can into the water until the dye floated out. After an interval to allow surface tension effects caused by the alcohol to die away, the initial measurement of dye concentration was made by slowly coasting the boat through the visibly-heaviest part of the dye patch. Slow coasting with the screw stopped allowed the boat to pass through the dye with little if any artificial mixing.

Measurements of dye concentration were made with the ultraviolet fluorometer of Noble and Ayers (1961). In this instrument the fluorescence of the dye under ultraviolet light is measured photoelectrically and converted by calibration curve to concentration of dye. Colored water of the dye patch was pumped continuously through the fluorometer during each pass through the patch. Only

the highest concentration noted during each pass was recorded and used in dilution computations, to obtain the most conservative dilution figures.

The regular station for the setting of dye patches was in 11-12 feet of water, between the two sand bars, about 500 feet from water's edge, and off the north side of the plant property. We have no reason to think that dilution figures obtained off other parts of the plant property would be significantly different from those presented here (Table 2).

In Table 2 the incremental dilution between two successive passes through a dye patch was obtained by dividing the earlier dye concentration by the later. Cumulative dilution was obtained by progressive multiplication of the incremental dilutions. After each multiplication the product was rounded to the nearest whole number before the next multiplication.

In the dye dilution experiments deliberate effort was exerted to run experiments on the calmest days possible, for low wind and minimum wave action produce least mixing and dilution, hence giving "worst condition" figures for dilution. Effort was also directed to obtaining observations under winds from as many directions as possible. The experiment of 19 September was carried out because of our desire to see an offshore wind, not because the wind velocity was in the desirable range.

On 19 September the dye patch was estimated to be 0.9 mile southwest of the regular setting station when the two closely-spaced measurements were obtained. A loose connection in the fluorometer prevented earlier measurements, and developing seas

Table 2.

Results of Dye Dilution Experiments

Time since set	Dye Concentration	Incremental Dilution	Cumulative Dilution
19 September 1966	Wind NE, 20 mph	Set at regular station	
2 hrs 15 min	2.1×10^{-8}		
2 hrs 22 min	1.2×10^{-9}	17.5X	18X (7 minutes)
25 October 1966	Wind NW, 5 mph	Set at regular station	
0 hrs 34 min	2.1×10^{-5}		
1 hrs 35 min	8.9×10^{-7}	23.6X	24X
2 hrs 45 min	1.1×10^{-7}	8.1X	194X
3 hrs 45 min	4.3×10^{-8}	2.5X	485X
4 hrs 50 min	2.45×10^{-9}	17.6X	8536X
5 hrs 45 min	2.45×10^{-9}	1.0X	8536X
25 October 1966	Wind NW, 5 mph	Set outside outer bar	
0 hrs 08 min	1.0×10^{-4}		
1 hrs 08 min	1.05×10^{-6}	95.2X	95X
2 hrs 23 min	2.25×10^{-7}	4.7X	447X
3 hrs 23 min	8.1×10^{-8}	2.8X	1252X
4 hrs 38 min	4.3×10^{-8}	1.9X	2379X
5 hrs 23 min	1.82×10^{-8}	2.4X	5710X

Table 2. (Cont.)

Time since set	Dye Concentration	Incremental Dilution	Cumulative Dilution
26 October 1966	Wind SSW, 5 mph	Set at regular station	
0 hrs 10 min	1.18×10^{-5}		
		67.4X	
1 hrs 22 min	1.75×10^{-7}		67X
		1.4X	
2 hrs 20 min	1.28×10^{-7}		94X
		1.6X	
4 hrs 40 min	8.2×10^{-8}		150X

spoiled later attempts by causing the fluorometer intake to capture air bubbles. The very rapid dilution being undergone by this dye patch illustrates the greater mixing effect of higher winds.

Sufficiently calm weather did not coincide with availability of the boat until late in October. At this time successful dilution experiments were run on 25 and 26 October. A run attempted under 20 mph winds from the southwest on 27 October failed because the dye was moved across the inner bar into water too shallow for the boat to reach it.

The alongshore current directions shown by the dye patches are reported in the section on local currents.

On the basis of the data available, there appears to be a reasonable dilution rate inherent in the natural regimen of alongshore currents. The natural regimen will, however, be modified to a degree by the current created by the flow of plant effluent.

3. LOCAL TEMPERATURE CYCLES

The Annual Cycles of Water Temperature

From our own data collected in connection with other types of investigations, we have assembled the surface water temperature curves shown in Figure 8.

Though our ships cannot operate in winter to measure temperatures, each winter produces ice in the rivers, in the alongshore waters, and floating ice-fields in the open lake. The presence of ice indicates that 32° F can be taken as a basic surface-water temperature at the beginning and end of the year. Use has been

made of this in the annual temperature curves.

Figure 8 presents surface-water temperatures from midlake stations during the relatively cool year of 1965, the relatively warm year of 1966 and from inshore stations in 1966. The midlake stations were our stations A-3, A-4, and A-5 in about the center third of the lake on a line from Benton Harbor to Chicago. The inshore stations were our stations B-1 and B-2 off South Haven, A-1 and A-2 off Benton Harbor, NB-1 and NB-2 off New Buffalo, and GA-1 and GA-2 off Gary, Indiana. These inshore stations all are at less than 10 miles from shore.

The curves all demonstrate an abrupt temperature increase in April, May and June and a steady, almost linear, decline from the peak of temperature in July or August to ice-water temperature in late December.

By mid-summer the thermocline has developed and worked down to more than the 20 feet at plant intake depth, and surface temperature in mid-summer and early fall represents the entire depth at the intake.

The 1966 annual curve of inshore temperatures is the present best estimate of ambient water temperatures against which the plant will have to operate. We suspect that this curve will better fit conditions at the plant site if it is shifted to the right to accord with one observation of 73° F at the site on 13 September 1966.

The basic ability of the local environment to remove thermal load from the plant effluent will probably be best measured by the difference between the annual air-temperature curve for 1966

and the inshore water-temperature curve of Figure 8 when shifted to the right as suggested above.

In cool years the inshore temperature will probably be lower by the difference between the 1966 and 1965 midlake curves.

4. LOCAL POTABLE WATER INTAKES

Potable water intakes in the southeastern portion of Lake Michigan are, from South Haven, Michigan, to Michigan City, Indiana:

South Haven:
Rated Capacity -----; present pumpage 1.7 mgd (1966 ave)*
Intake Locations: 2500 ft off beach, 25 ft deep over crib**
254° true from pierhead light**

5700 ft off beach, 34 ft deep over crib**
237° true from pierhead light**

"5650' of 24" intake 40' deep"*

Benton Harbor:
Rated Capacity 12 mgd; present pumpage ca 6 mgd***,
3.7 mgd (1966 ave)*
Intake Locations: 3500 ft from beach, 27 ft deep over crib**
6200 ft 022° true from pierhead light**

"3375' of 36" intake 40' deep"*

St. Joseph:
Rated Capacity 8 mgd; present pumpage 7 mgd***
3.21 mgd (1966 ave)*
Intake Locations: 1500 ft off beach, 13 ft deep over crib**
6700 ft 197° true from pierhead light**

"1490' of 24" intake 19' deep"*

Bridgman:
Rated Capacity 1.4 mgd; present pumpage ca 0.5 mgd***
0.315 mgd (1966 ave)*
Intake Locations: 800 ft off beach at the end of Lake St.**
Infiltration system with 350 ft of collectors***

"radial collector intake at edge of Lake Michigan"

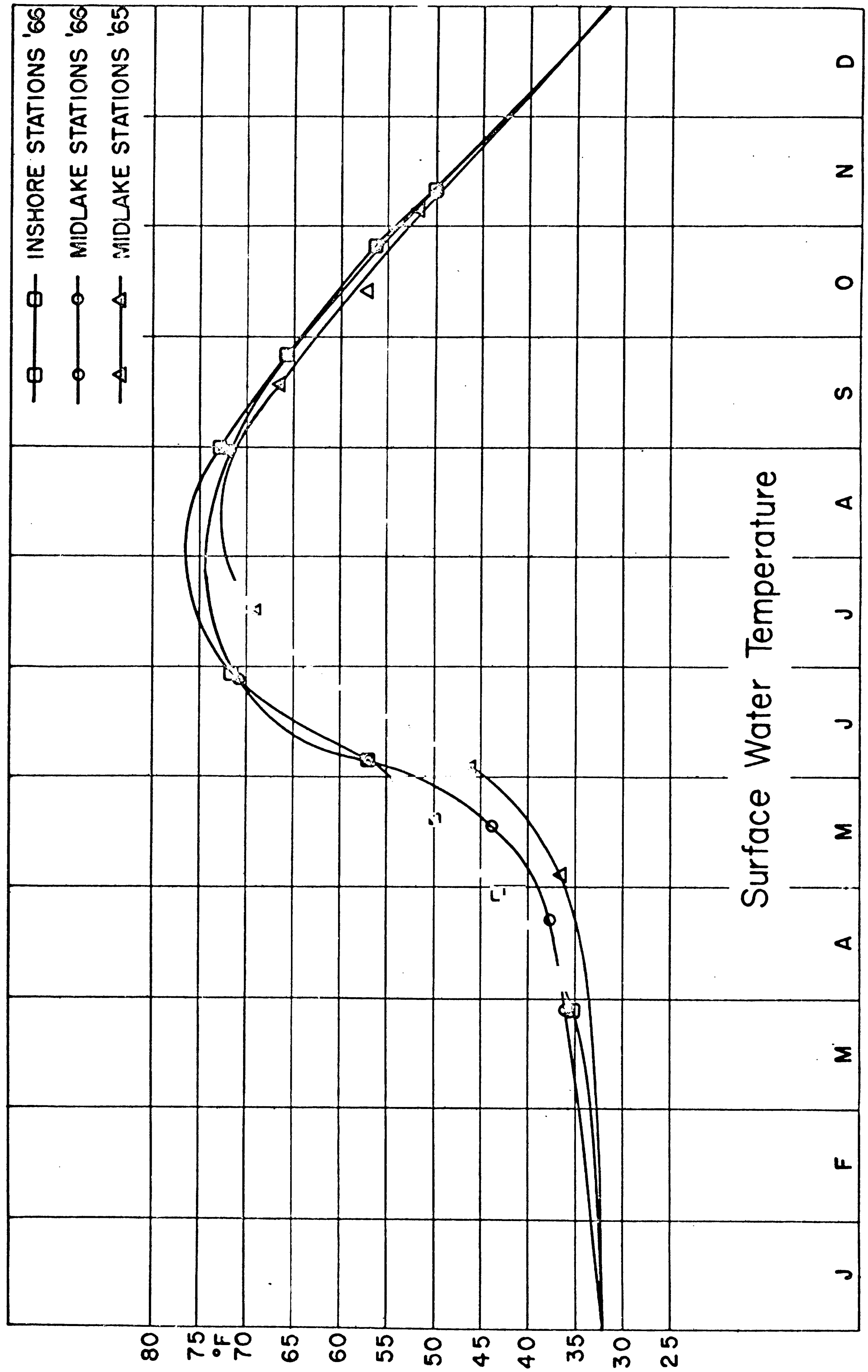

INSHORE STATIONS '66
MIDLAKE STATIONS '66
MIDLAKE STATIONS '65
Surface Water Temperature
°F
80
75
70
65
60
55
50
45
40
35
30
25
J
F
M
A
M
J
J
A
S
O
N
D

FIG. 8

Orchard Beach: (subdivision in Chickaming Township, near Sawyer)
Rated Capacity -----; 0.125 mgd (1966 ave)*
Intake Location: "Infiltration lines at edge of Lake Michigan"*

New Buffalo: (new plant just being completed)
Rated Capacity 14 mgd; present pumpage (not from lake) 6 mgd***
Intake Location: 3000 ft off beach at Sunset Shores at west end of city***

Grand Beach:
Rated Capacity -----; 0.250 mgd (1966 ave)*
Intake Location: "Infiltration lines at edge of Lake Michigan"*

Michiana:
Rated Capacity -----; 0.275 mgd (1966 ave)*
Intake Location: "Infiltration lines at edge of Lake Michigan"*

Unknown: (intake and tank between Michiana and Michigan City on Chart 75)
Intake Location: 1000 ft from shore in 6 ft of depth**

Michigan City, Indiana:
Rated Capacity 20 mgd; present pumpage 7 mgd***
Intake Locations: 2300 ft off beach, 29 ft deep over crib**
3300 ft 050° true from East Pierhead Light**

2500 ft off beach, 35 ft deep over crib**
3900 ft 053° true from East Pierhead Light**

2600 ft off beach, 24 ft deep over crib**
4200 ft 054° true from East Pierhead Light**

*From pp. 30-31 of Michigan Water Resources Commission: "Water Resource Uses Present and Prospective for Lake Michigan and Proposed Water Quality Standards and Plan of Implementation" Feb. 1967.
**From U. S. Lake Survey Chart No. 75.
***Personal Communications, plant operators to J. C. Ayers, Nov. 1 and 3, 1966.

Intake locations referenced to pierhead lights have been done by us from U. S. Lake Survey Chart No. 75. The pierhead lights used are the dominant ones, as identified by the greatest range of visibility given on that chart.

Distances from the center of the plant site frontage to the several potable water intakes have been measured along the waterline

of U. S. Lake Survey Chart No. 75. They are, to the nearest half-mile:

Distances North:	
South Haven	32 miles
Benton Harbor	11 miles
St. Joseph	9 miles
Distances South:	
Bridgman	2-1/2 miles
Orchard Beach	ca 7 miles
New Buffalo	16 miles
Grand Beach	18 miles
Michiana	19 miles
Unknown	22 miles
Michigan City	25 miles

To the north the outflow of the St. Joseph River interposes a physical and dynamic barrier to further progress of effluent northward along the shore. The river effluent turns northward under southerly winds and interposes itself between the beach and the current from the south, which has to swing out around the breakwaters. Mixing between river and alongshore current, also, begins at the tip of the breakwaters.

For reasons discussed in a later section we believe that cooled and diluted effluent from the plant could, under light-wind conditions when plumes are more coherent and less diluted, reach the water intakes at Bridgman and at Orchard Beach.

In the cases of Bridgman and Orchard Beach, there appear to be two circumstances contributing to minimization of nuisance from arrival of the plant effluent. First, on the basis of present evidence, the southerly and southwesterly prevailing winds of summer (when worst conditions may be expected) produce <u>northward</u> currents that will carry the effluent away from Bridgman

and Orchard Beach. Second, these communities' buried collectors together with temperature lags inherent in collection systems should reduce and smooth temperature variations in their raw water supplies.

Icing of Water Intakes

We cannot contribute to this subject anything in addition to, or more pertinent than, the facts that the superintendents of the Benton Harbor and St. Joseph water plants in telephone conversations have both stated that their plants encounter no difficulties with icing of intakes during winter.

5. SEICHES

In this section we follow the usage of the American Meteorological Society as set forth in their Glossary of Meteorology: "In the Great Lakes area, [a seiche is] any sudden rise in the water of a harbor or a lake, whether or not it is oscillatory. Although inaccurate in the strict sense, this usage is well established in the Great Lakes area."

A series of three articles by Platzman, Irish, and Hughes in Monthly Weather Review, volume 93, number 5, May 1965, and a report by the Illinois Division of Waterways in 1958 serve as sources of much of the below as well as giving references to other pertinent literature.

The records indicate that there are frequent small seiches of a few inches amplitude. These are not regarded as being of importance.

Of definite importance, however, are larger seiches associated with the passage of large line-squalls from northwest to southeast across Lake Michigan. These squalls have their fronts oriented NE-SW and are accompanied by an abrupt increase in barometric pressure and local high winds. The combination of air pressure increase and wind pressure depresses the water surface under the storm front and starts a forced wave running southeastward across the lake. If the speed of progression of the front is 40 mph or more, the forced wave is in or near resonance with one of the natural modes of the southern basin and the wave is reinforced as it crosses the lake. Bottom friction slows the progress of the south end of the wave and it arrives on the southeastern shore with a shape convex toward the southeast. The faster deep-water north end of the wave appears to strike obliquely along most of the Michigan shore without causing water-level rises much more than its own height, but in the southeast corner of the lake the wave shape is nearly parallel to the shape of the shore and additional rise of level is caused as the translated water of the wave is trapped against the shoreline. From the southeastern corner the wave is then reflected, with additional shallow-water refraction, westward across the lake to the Chicago region.

The largest of the recent large seiches or storm surges occurred on 26 June 1954. It caused some damage in Michigan City and both damage and loss of life in Chicago, consequently it has been studied in detail and its causes and behavior recognized. The U. S. Weather Bureau Station at Chicago now issues seiche predictions routinely when conditions justify.

The available figures about water levels of the 26 June 1954 seiche are:

Level variation of 3.2 feet at Wilson Ave. Crib (Chicago)

10	feet rise of water level at	North Ave. (Chicago)
8	" " " " " "	Montrose Harbor (Chicago)
2.4	" " " " " "	Chicago River mouth
2	" " " " " "	Waukegan, Ill.
6	" " " " " "	Michigan City, Ind.

It appears that all these figures, except that for Michigan City, are from the wave reflected from the eastern shore; the Wilson Ave. Crib figure probably can be taken as indicative of the height of the deep-water wave involved in the Michigan City and Chicago regions as can that for Waukegan for that area; higher figures represent trapping of the wave by harbor structures or local shoreline configurations.

Data for other seiches large enough to have been noticed and recorded are:

19 August 1921, Milwaukee, Wisc.
Water rose 1.5 feet and fell 1.0 feet all within a half hour.
A few hours later the water fell 2.0 feet in 10 minutes.

21 June 1954, Chicago, Ill.
Water level variation of 1.3 feet at Wilson Ave. Crib.

6 July 1954, Chicago and Waukegan, Ill.
Level variation of 4.2 feet at Wilson Ave. Crib.
" " " 4.1 " " Waukegan.

3 August 1960, Chicago and Wilmette, Ill.
Water rose 2.5 feet at Wilmette.
" " 4.0 " " Montrose Harbor.
" " 3.0 " " Belmont Harbor.

On the southeastern shore the seiche arrives with the squall-line passage. The seiche does not have the rapidity or damaging power of a wind-wave of equal height. Instead, the rise of water is continuous over several minutes, and damage is primarily due to flooding. Loss of life appears to be confined to non-swimmers

who do not notice the rising water until too late; pier fishermen and children playing at the water's edge being the chief victims.

Within the bounds of the seiche-causing conditions, it may be assumed that a line squall from a direction west of northwest might have a progress velocity sufficient to match the mode of the southern basin and to produce a seiche-front so shaped as to trap against shore at the site. The maximum open-lake seiche of record is the 4.2 feet at Wilson Ave. Crib on 6 July 1954 above. Proportioning from the 3.2 foot rise at Wilson Ave. Crib on 26 June 1954, which produced 6 feet of seiche at Michigan City, it appears that maximum seiche at the plant site would be of the order of 8 feet.

C. DILUTION AND DISPERSION OF THERMAL EFFLUENT

Operation of the proposed plant will produce a "river" of warmed effluent in a region where none existed naturally. The flow of this "river" is expected to go from an initial one-unit-in-operation condition of 1200 cfs to about 4000 cfs at possible ultimate 4-unit operation.

Since it is anticipated that the dilution of nucleid wastes to the level required for public safety will be accomplished before the effluent is released to the lake, the problem becomes one of estimating future dispersion of future thermal waste in future effluent.

For the estimation of the dispersion of the future plume of warm effluent water, probably the best model is the behavior of natural river effluents.

The available studies of natural river effluents are for rivers of about 4000 cfs flow, and the studies are not sufficiently advanced to enable us to scale down to the 1200 cfs flow of the initial one-unit plant. The discussion in this section is, then, for the possible ultimate 4-unit plant, and is over-pessimistic for the case of the one-unit plant. The discussion is also conservative in that lack of data force us to treat of plume length at the vanishing point, rather than to a point of a few degrees of residual heat that would pass unnoticed.

From mid-spring until the height of summer, river effluents are commonly warmer than the receiving lake water. River effluents emerging through river mouths become immediately subjected to the directional and dispersive actions of wind and alongshore currents. The river-effluent model contains the basic desiderata of the plant effluent problem, except that temperature differences between river and lake are usually not so gross as will be those between plant effluent and lake.

For nearly a year we have required our ships to log wind direction and direction of turn of river effluent each time they enter or leave a river mouth. In all the cases yet seen, the river effluent has turned downwind immediately after leaving the river mouth.

On several occasions we have tried to follow the effluent of the Grand River whose mean summer flow is about 4000 cfs (Horton and Grunsky 1927). In every case we have lost visual (color), thermal, and turbidity or conductivity evidence of river water within three miles of the river mouth. Similar, but fewer, attempts

to follow the plume of the St. Joseph River whose flow reaches 4000 cfs on occasion (Cook and Powers 1964), have given the same result.

Since we began recording river-mouth temperatures in the spring of 1966, the greatest observed difference between river-mouth surface water temperature and open-lake surface water temperature was 20° F. This was observed at the mouth of the Kalamazoo River at Saugatuck, Michigan, on 1 June 1966. From what we have been told of the thermal load to be carried by the plant effluent, we expect its temperature increment of 25° F to lie on the high side of the range of natural-river to open-lake surface temperature differences.

In making the following rough estimates of probable length of the plume of effluent, under "worst" conditions of light wind in the height of summer, we have assumed that the spread of the effluent plume will not be greatly different from that of natural river plumes in summer. We have further assumed that the summer flow rates of the Grand and St. Joseph Rivers adequately represent the full-operational plant effluent which we are told will be 4000 cfs.

It appears to us that the major difference between a natural river plume discharged through breakwaters and the plume of the artificial river of effluent from the plant is that the latter will probably be discharged near the natural shoreline and, in its worst condition, will run along shore in shallow water where only limited amounts of cool diluting water will be available. The length of the effluent plume should, then, vary from that of

natural river plumes inversely as the mean depths along their lines of flow.

From the charts we have taken 20 feet as the mean depth along the flow paths of the plumes of the Grand and St. Joseph when these run parallel to shore. We have estimated the mean depth between the beach and the outer sand bar to be eight feet. It is deemed reasonable in this first approximation to take all other conditions as being equal.

Using the maximum observed river plume length as three miles and multiplying by the inverse depth factor, 20/8 or 2.5, we obtain an approximated length of effluent plume of 7.5 miles.

Another rough first approximation can be made from the flow-content of natural plumes and topographic conditions at the plant site.

Taking 0.2 mph as a mean "worst condition" light-wind current speed at a quarter mile from shore, as was found in the drogue runs off Palisades Park described above, we may divide into the three-mile maximum river plume and obtain the estimate that the maximum natural plume contains about 15 hours of river flow. Taking the outer sand bar to lie at 1000 feet from shore, and estimating the mean depth between the outer bar and shore at eight feet, we obtain an approximate 8000 square feet as the cross-section available to effluent flow along shore. Dividing into 4000 cfs outflow, we obtain 0.5 feet per second as the indicated plume speed near the outfall under light-wind conditions. Assuming further that bottom friction will decrease the flow velocity along the length of the effluent plume to the natural 0.2 ft/sec (mean

velocity from sets inside the outer bar in Table 1), we have averaged the two velocities to obtain 0.35 ft/sec as the mean speed of effluent movement. Over 15 hours of unidirectional wind at this mean speed the plume should reach to a distance of 5.25 miles.

Since both these estimates are preliminary, we take the mean (6.4 miles) as a second approximation of the distance to which the plume of plant effluent might reach before vanishing under light-wind alongshore-current conditions. Refined current velocity data from our 1967 work may permit recomputation of these estimates. If so, they will be amended.

Though the second approximation is preliminary, it is unlikely that plant effluent would reach the intakes at St. Joseph (9 miles), New Buffalo (16 miles), Grand Beach (18 miles), or Michiana (19 miles). Because of the protection afforded by the outflow of the St. Joseph River, described previously, it appears unlikely that plant effluent would reach the Benton Harbor intake at 11 miles distance.

It appears probable that cooled and diluted plant effluent could reach the intakes at Bridgman (2-1/2 miles) and Orchard Beach (ca 7 miles) under the occasional northwest winds of summer, but summer northwest winds are cool and usually not light in velocity. The infiltration collectors at Bridgman and Orchard Beach would appear to have certain inherent protective characteristics already mentioned.

Under the conditions we have so far observed at river mouths, the river water reaches to the lake bottom for a short distance

beyond the tips of the breakwaters, after which it begins to be buoyed up by the colder denser lake water. We believe that the effluent's river-like tendency to reach to bottom at the mouth of the outflow channel will result in some erosion of the inner sand bar in front of the outflow channel. We believe that the whole of the area between the outflow channel mouth and the second (outer) sand bar will be filled with effluent water before buoying-up by lake water begins. We believe that from this effluent-filled area in front of the plant the plume of effluent will depart in the downwind direction. In the cases of winds producing alongshore currents, we believe the effluent plume will depart laterally from this filled area, guided by the sand bars.

When there is no wind the effluent should pond in front of its outflow channel and drift slowly away with what residual current remains from the last wind. Under this condition the dispersion of the effluent should be expected to be minimal. Because of this, the percentage of calms becomes an operationally-important meteorological parameter.

Strong winds from directions from south through west to north should greatly aid the dispersal of the effluent plume and the removal of its thermal load. The frequency of strong winds from these directions becomes also an important meteorological parameter.

During calms and light winds the convection of sensible heat to the atmosphere will probably be the most important mechanism for disposing of the thermal load carried by the plant effluent. An annual curve of air temperature (for comparison against the curves of water temperatures shown in Fig. 8) becomes an important

meteorological parameter in determining the probable seasonal ability of the air to withdraw thermal load from the plant effluent.

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